An Explanation of Yield Differences in Three Potato Cultivars

J. S. Oliveira,* H. E. Brown, A. Gash, and D. J. Moot

ABSTRACT

Under ideal growing conditions, yield is the product of intercepted photosynthetically active radiation (PAR_i) and its conversion efficiency to dry matter (radiation use efficiency, RUE). For potato (*Solanum tuberosum* L.) the ability of the leaf to convert the PAR_i into carbohydrates (source) and the storage capacity of the tubers (sink) affect the potential growth of individual tubers and therefore crop yield. This study describes these mechanisms for three commercial potato cultivars (Bondi, Fraser, and Russet Burbank) grown in non-limiting field conditions. At final harvest Bondi had the largest tuber yield and produced heavier but fewer tubers compared with Fraser and Russet Burbank. All crops had similar total accumulated radiation interception (R_{cum}), and yield differences were explained by the RUE which was highest for Bondi, lowest for Fraser, with Russet Burbank intermediate. Fraser had the lowest rate of canopy senescence, maintained the lowest specific leaf area (SLA) for most of the period of tuber bulking and maintained the highest dry matter (DM) allocated to leaves at the end of the tuber filling phase. Throughout the crop growing period Bondi had a larger tuber sink compared with Fraser and Russet Burbank. These results suggest that potato tuber production was limited by the "sink strength" and RUE in the lower yield varieties. The larger sink in Bondi, caused by shorter stolons, enabled higher rates of tuber filling which produced the largest tubers in the middle node positions and the highest average tuber weight per plant among these cultivars.

Core Ideas

- The tuber yield of three potato cultivars was compared.
- Yield differences were not determined by total intercepted radiation.
- Low tuber sink strength and a low radiation use efficiency were detrimental to tuber yield.
- Leaf photosynthesis down regulation was linked to specific leaf area and canopy longevity.
- Final stolon length was the first vegetative signal of tuber sink strength during plant growth.

Potato is a staple crop worldwide, ranking fourth after maize (*Zea mays* L.), rice (*Oryza sativa* L.), and wheat (*Triticum aestivum* L.). As potato consumption increases there is a need to understand the mechanisms that drive its yield. However, the origins of yield differences are rarely made clear in cultivar comparisons (Van Der Zaag and Doornbos, 1987) and breeding programs.

Potato crop growth and tuber yields have been linked to the duration of the growth cycle, which depends on climate, cultivar, and crop management (Kooman et al., 1996a, 1996b). Therefore, assuming optimum crop management, differences in tuber yield among potato cultivars can be explained by differences in accumulated intercepted radiation, the utilization coefficient of foliage followed by DM distribution within the plant (Van Der Zaag and Doornbos, 1987). Indeed, the amount of radiation intercepted by a crop and the RUE provide a useful basis for investigating yield variation (Monteith, 1977). From this concept, a simple model to express potato DM growth has been reported (Jamieson et al., 2004) as:

$$Y = \int_{em}^{t} (R_o \times R/R_o \times \mathrm{RUE}) \times \mathrm{HI} \qquad [1]$$

where Y is the tuber yield, R_o is the daily incident solar radiation received, R/R_o is the daily fraction of R_o which is intercepted by the canopy (R being the daily average radiation intercepted by the plant), and RUE is the overall photosynthetic efficiency of the crop (i.e., the efficiency of conversion of radiant to chemical potential energy). The HI is the fraction of the dry matter produced which is allocated to the tubers. The integration of these components over time (t; days) from crop emergence (em) allows the description of biomass accumulation in terms of plant development processes.

This is a common approach used for potato yield analysis (Van Der Zaag and Doornbos, 1987; Spitters et al., 1989; Ellissèche and Hoogerndoorn, 1995) and simulation models of potato yield (Jamieson et al., 2004). The amount of radiation intercepted by the crops is reportedly the central component to explain

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J.S. Oliveira, A. Gash, and D.J. Moot, Faculty of Agriculture and Life Science, P.O. Box 85084, Lincoln University, 7647, Canterbury, NZ; H.E. Brown, The New Zealand Institute for Plant and Food Research Ltd., Private Bag 4604, Christchurch, NZ. *Corresponding author (juliano.oliveira@lincolnuni.ac.nz).

Abbreviations: DAP, days after planting; DM, dry matter; LGR, linear growth rates; R_{cum}, accumulated radiation interception; R/R_o, radiation interception or fraction of canopy ground cover; RUE, radiation use efficiency; SLA, specific leaf area.

cultivar yield differences. However, there has been little potato research to define the ideal canopy structure for obtaining high and stable tuber yields (Schittenhelm et al., 2006). Differences in RUE among genotypes are usually unclear (Jefferies, 1993) and therefore it is often assumed as a constant value in potato simulation models (Griffin et al., 1993; Van Keulen and Stol, 1995). This simplification may compromise the precision of yield simulations when RUE deviates from a fixed value. Moreover, there is little information on the partitioning of photosynthates within the plant organs before and after the tubers become the largest sink in the plant. This represents another weakness in potato yield models. Kooman and Rabbinge (1996), for example, suggested that leaf production and longevity in potato crops are regulated by tuber sink strength. This suggests the importance of accounting for the impacts of sink strength on mechanistic potato modeling approaches. In fact, potato models frequently consider a phase when leaf growth and tuber bulking overlaps (Griffin et al., 1993; Kooman and Haverkort, 1995). During this period there is competition between foliage and tubers for assimilates. Therefore, it seems that an accurate description of source capacity and sink demand during this phase is important to understand potato crop physiology that could then be utilized to inform potato crop models and improve understanding of potato yields.

In this research, aboveground and belowground growth behavior of three potato cultivars are reported from field grown conditions. Comparisons of canopy development and, radiation interception, RUE, and DM partitioning to tubers and aerial organs are made to explain yield differences among cultivars. The relationship between individual tuber growth, node position, and stolon length, to which the tuber is attached, are also described.

MATERIALS AND METHODS

Experimental Site and Meteorological Data

The experiment was located in Canterbury, NZ (43°39′ S and 172°28′ E). The paddock was in grazed pasture prior to the establishment of these potato crops. The soil is classified as a Templeton silty loam (or Udic Ustrochrept), Typic immature pallic soil, characterized as moderately deep (45–90 cm) with 102 mm available water in the top 0.6 m.

Hourly values of maximum and minimum air temperatures and daily values of total radiation, actual rainfall, and evapotranspiration were obtained from data recorded at Broadfields Meteorological Station at Lincoln, Canterbury, NZ, located within 1.5 km from the experimental field. Mean monthly air temperature (°C) ranged from 6 to 15°C during the experiment. The largest daily temperature difference occurred in November when the temperature ranged from 0 to 27°C (see Appendix A for details of daily minimum, maximum, and average air temperatures). The average monthly solar radiation ranged from 6.5 MJ m^{-2} for the month of May to 24 MJ m^{-2} for the month of November.

Cultivars

Two New Zealand grown cultivars of contrasting yields (Bondi and Fraser) and an internationally known standard (Russet Burbank) were used. These are all maincrop potato cultivars with an indeterminate growth habit.

Seed Potato Origin, Storage, and Field Planting

A total of 348 seed potatoes of each cultivar were collected from three different locations in mid-Canterbury and then stored under commercially accepted best practices in a cooler (4°C) for ~14 d after each crop was machine harvested. On 9 Sept. 2011 (~28 d before planting) all seed potatoes were moved from the cooler into a shed (at ambient temperature and no light) to break dormancy. The mean seed potato weight was similar to commercial standards (~115 g for Bondi, ~80 g for Fraser and ~115 g for Russet Burbank) and these seed potato weight differences are not expected to contribute to differences in crop yields (Oliveira et al., 2014; Oliveira, 2015).

A field experiment was established to compare the growth and development of each crop under optimum conditions on 0.031 ha. Best management practices were applied to keep the crop free of weeds, pests, and diseases and supplied with adequate nutrients and water (see Appendix B for details). On 14 Oct. 2011 the seed potatoes were hand planted and mechanically molded to ~300 mm of depth. Plots were 21 m long and 1.6 m wide with two rows. Plant spacing was 0.35 m within the same row and 0.8 m between rows, with each cultivar planted in three replicates following a completely randomized design. Plots were separated by a 1.6 m empty row. In addition, two buffer plants were used at the end of each plot row.

Morphological Definitions and Crop Measurements

In this paper a main stem refers to the "true stem" developed directly from the seed potato as defined by Vos (1995) and Struik and Ewing (1995). Belowground level, each main stem can develop stolons and belowground lateral branches (BGLB) from its axillary nodes. Stolons are diageotropic stems with elongated internodes and may bear tubers. The report of tuber length at the node level will refer to individual tubers produced at a certain node position on the main stem (belowground level). Aboveground level, the same main stem produces a leaf and potentially a branch at each node (first level of foliage) which terminates in an inflorescence (first inflorescence). Lateral branches are also produced on these main stems above the ground level. These aboveground lateral branches can arise on the second (n-1) and third (n-2) axillary nodes below the first inflorescence (apical lateral branches) and at lower node positions (e.g., n-13 and n-14; basal lateral branches) of the main stems. These aboveground lateral branches represent the second level of growth that can also terminate in an inflorescence (second inflorescence). Later, third and higher levels may appear (refer to Appendix C for schematic illustration of the potato plant organs).

In this study the top most aboveground lateral branch (n-1 or n-2) to appear on each new level of growth was considered as a continuation of the main stem. Therefore, values reported for the main stem measurements aboveground level (e.g., number of leaves, leaves DM, petiole DM and "stem" DM) include the main higher order lateral stems. The term aboveground "stem" will be used to designate any stem above the ground level without petioles, leaves, and flowers.

The date of 75% emergence was determined in all replicates by counting the number of plants emerged over the whole plot every second day. A plant was defined as emerged at the first appearance of a leaf above the ground (Searle, 1999). All DM

measurements were obtained after drying the samples in a forced air oven (65–70°C) to constant weight.

Fractional Radiation Interception

A multispectral radiometer system (CROPSCAN, Inc., Rochester, MN) was used to estimate the percentage of canopy cover or fraction of radiation interception (R/R_o) at a 7 to 20 d interval from 18 Nov. 2011 to 13 Apr. 2012. Reflectance of the radiation in the visible (VIS; 400–700 nm) and in the near infrared (NIR; 750–850 nm) wavelengths was combined to the normalized difference vegetation index (NDVI) to give the canopy intercepted radiation (R) at each CROPSCAN reading. These values were later combined with the total incident radiation (R_o) to give the fraction of radiation interception by the crop, or crop canopy cover (R/R_o) (Tucker, 1979; Gamon et al., 1995). Appendix D has more details on NDVI measurements and calculations.

Sampling

Six plants were sampled from each plot (three plants on each row). The plants were hand lifted using a fork on 11 occasions (40, 47, 53, 61, 67, 75, 82, 97, 111, 125, and 138 days after planting [DAP]) from 23 Nov. 2011 to 29 Feb. 2012. The first to the fifth samplings were scheduled to occur between the phenological stages 40 to 41 (BBCH-scale), the 6th to the 10th samplings between 41 and 47 (BBCH-scale) and the 11th sampling on 48 (BBCH-scale). The samples were taken sequentially from the western end of each plot. To minimize any confounding effect of canopy competition among plants, the first plant of the row was skipped at each sampling event. The plants were hand lifted with care using a fork to preserve the stolons attached to the tubers and to the main stems. Later the bulk of soil around the belowground organs was removed by hand. A subsample of one main stem of each plant (with all its aboveground and belowground organs) was randomly selected from each one of the six plants sampled. The subsample was then separated into aboveground and belowground organs, and DM recorded.

Aboveground Organs

The measurements taken from the subsample main stems included individual green leaf area, individual green leaf DM (without the petiole), petiole DM and main stems DM.

To measure individual leaf area a Li-Cor 3100 Area Meter (LI-COR, Lincoln, NE) was used. The leaves from each individual node of the main stem were grouped from the six subsamples before going through the leaf area meter.

Belowground Organs

For the whole sampling period, the belowground sample DM (including stolons and excluding roots) was measured. In addition, for all 11 sampling events, the tubers collected from the destructive sample (including the tubers from the subsamples) were washed and left to air dry before being weighed fresh (FM). Then, the tubers were dried to obtain DM on each sample.

A ruler was used to take some measurements on the subsample. These measurements focused on stolons grown on the individual nodes of the belowground main stem and on the tubers grown from these stolons. To achieve this, each node position was numbered from top (near ground surface) to bottom on the belowground main stem profile. The nodes were then measured for stolon length and visually assessed for tuber initiation status. The stolons were also classified according to their origin: primary and lateral stolons were those arising from primary and associated axillary nodes at belowground nodes, respectively, while stolons originating as branches of primary stolons or secondary stolons are referred to as "branch" stolons (Cother and Cullis, 1985). Tuber initiation was considered from when the tip of the stolon started swelling (2 mm of width). From the swelling stage onward the potato crops were graded into size classes of 1 cm. These measurements at the individual node position level were last taken on 4 Jan. 2012 for Bondi and on 19 Jan. 2012 for Fraser and Russet Burbank. After those dates the tubers detached easily from stolons and, therefore it was impossible to lift the entire crop with all of the tubers still attached to each stolon, to be completely sure of its origin.

On 18 Apr. 2012 the three cultivars were desiccated after they all had reached more than 50% of canopy senescence. The experiment ended when the potato plants were mechanically harvested on 2 May 2012 using a single row digger. On this occasion, around 36 plants (or 30% of the total number of plants sown per plot) were harvested from each plot.

Calculations

Tuber Yield

The final tuber yield distribution of each cultivar was calculated based on the accumulated proportion of final yield. To calculate the accumulated proportion of final yield the tubers were sorted into weight grades of 50 g. The sum of weights within each grade divided by the total FM (of all tubers) gave the proportion per grade. The sum of grade proportions from the lowest (0–50 g) to the highest (1050–1100 g) grade established the accumulated proportion which ranged from zero to one.

Accumulated tuber DM yields (measured from 23 Nov. 2011 to final harvest) were fitted against DAP and growing degree days (GDD) using a Gompertz curve:

$$y = a \times \exp\{-\exp[-b \times (x - c)]\} \quad [2]$$

where y is the tuber mass, a is the maximum tuber mass, b is the relative growth at the inflection point and c is the time (e.g., GDD) at the inflection point. The time when 5% and 95% of the final tuber DM was also calculated for each plot based on the curve estimates. Linear growth rates (LGR) and tuber DM ha^{-1} $°Cd^{-1}$ were also calculated for each plot of each cultivar. The LGR was calculated by fitting a linear regression between accumulated tuber DM and GDD using all datapoints within the range of 5 and 95% of the maximum yield for each cultivar (Brown, 2004).

Growing Degree Day Calculation

Daily GDD (°Cd) was calculated using daily average air temperatures (T_{mean}) after crop emergence. Daily average air temperature was measured using the average of hourly air temperatures above a threshold (T_b) of 2°C (Oliveira, 2015). Then the cumulative GDD was calculated by the sum of the daily GDD. A linear function of temperature accumulation with a rate of 1.0°Cd $°C^{-1}$ above T_b was applied. Since the T_{mean} was never above 25°C during the field experimental period, GDD did not have to be corrected for supra optimal temperatures.

Fractional Radiation Interception, Leaf Area Index, and Extinction Coefficient

The R/R_o was measured and combined with the total incident radiation (R_o) from the meteorological station to calculate the radiation intercepted in MJ m^{-2} by the canopy. Daily values of radiation interception (R_{daily}) were estimated with a Piece-wise regression fitted to each individual plot using a series of 16 measurements taken from 15 Nov. 2011 to 13 Apr. 2012. The regressions were fitted against DAP and GDD. The Piece-wise regression consisted of a three phase linear model of canopy formation. Immediately after crop emergence, the phase of canopy growth happened concomitant to the R/R_o rise at a linear rate of increase. Then the crop had a constant canopy phase when the crop was at maximum ground cover ($R/R_{o\ max}$). The final phase characterizes the canopy senescence in which R/R_o decreases at a linear rate.

The total accumulated radiation interception (R_{cum}) was calculated by integrating R_{daily} from crop emergence (em) to crop desiccation (des), on 18 Apr. 2012, according to Eq. [3]:

$$R_{cum} = \int_{em}^{des} R/R_{o\,daily} \times R_{o\,daily} \qquad [3]$$

where, R_{odaily} is the daily average total incident radiation.

Leaf area index (LAI) was estimated from leaf DM using the concept of specific leaf area (SLA; $m^2\ kg^{-1}$ DM of leaf). The extinction coefficient (k) was used to describe the canopy architecture of the crops. The k value was calculated from the regression of the natural log of the R/R_o by the crop against LAI.

Radiation Use Efficiency

Radiation use efficiency was calculated from the total dry matter (DM_{total}) accumulated in the entire plant (which included aboveground and belowground parts of the crop but excluded roots). The calculation fitted a linear regression from the origin, to the plot averages of DM_{total}, against R_{cum} from 14 Oct. 2011 to 29 Feb. 2012.

Fraction of Total Dry Matter Partitioned in the Tubers (Harvest Index)

The fraction of total DM partitioned in the tubers or crop harvest index (HI) was calculated by dividing the DM accumulated in the tuber by the DM_{total}.

Leaves, Petioles, and Aboveground Stems Dry Matter

The proportion of DM allocated to leaves, petioles, and aboveground main stems was estimated from the subsample measurements and then these were multiplied by the total DM of the sample (six plants = ~1.7 m^2) to give the DM of leaves per plant, petioles per plant, and aboveground stems per plant, respectively.

Data Analysis

Data were analyzed using GenStat version 14 (VSN International). Significant differences among the treatments were determined by ANOVA according to the completely randomized design. Standard error of differences of means (SEM) were used to evaluate least significant differences (LSD) at the $\alpha = 0.05$ probability level for means separation of the cultivars. Linear and nonlinear regressions were fitted between dependent and explanatory variables. When appropriate, a Piece-wise regression was fitted using SIGMAPLOT version 10.0 (SPSS Inc.). Regression coefficients, standard errors of coefficients and coefficients of determination are reported. When values are significant at $\alpha = 0.1$ but not $\alpha = 0.05$, results are reported as a trend.

RESULTS

Bondi had a larger ($P < 0.067$) tuber DM yield (~17.0 t ha^{-1}) than either Fraser (~13.3 t ha^{-1}) or Russet Burbank (~13.5 t ha^{-1}) at final harvest. This reflected the conservative tuber dry matter content (DM%) among the cultivars during the whole growing season. For all cultivars tuber DM% increase was described by a sigmoid curve from 15% (~50 DAP) to an asymptote at 26%, from ~140 DAP until final harvest.

There was also a strong ($R^2 > 0.99$) relationship between tuber DM and GDD accumulated from crop emergence (Fig. 1). Tuber DM increased consistently from ~370°Cd (or 62 DAP), when 5% of the final tuber DM was reached in all cultivars, to ~1400°Cd (or 140 DAP). At this point the three cultivars had attained 95% of the final tuber DM yield and therefore this was considered the final tuber yield (Fig. 1). The average rate of maximum tuber DM accumulation (LGR) was ~20% higher ($P < 0.02$) for Bondi (1.58 kg ha^{-1} °Cd^{-1}) than Fraser (1.26 kg ha^{-1} °Cd^{-1}). Refer to Appendix E for LGR linear equations.

Bondi had a higher total yield compared with Russet Burbank and Fraser, but these last two produced 57 and 70%, respectively, more ($P < 0.01$) tubers than Bondi (27.8 tubers m^{-2}). (Refer to Appendix F for marketable tuber grade yields and yield numbers.)

Figure 2 shows the accumulated proportion of yield screened into 50 g grades. Fraser and Russet Burbank showed similar yield distributions with 75% of their FM yield in potatoes of grades under 250 g. In contrast, potatoes that weighed less than 250 g accounted for only 25% of the Bondi yield. For Bondi, 50% of

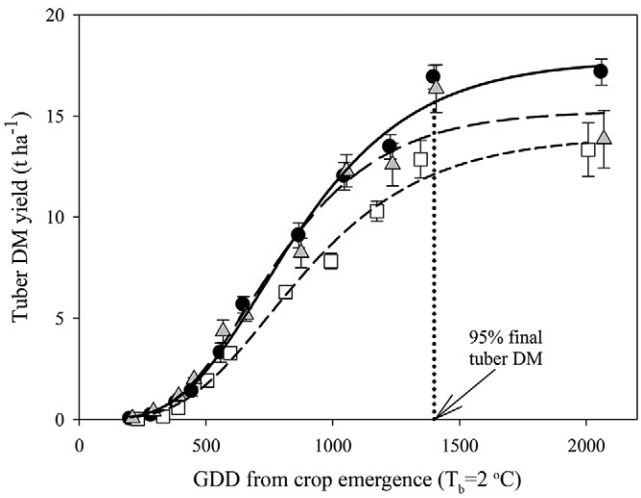

Fig. 1. Average potato dry matter (DM) against growing degree days (GDD, T_b = 2°C) for Bondi (closed circle), Fraser (open square) and Russet Burbank (shaded open triangle) crops planted on 14 Oct. 2011 at Lincoln, Canterbury, NZ. Gompertz curves are: Bondi: $y = 17.8 \times \exp\{-\exp[-3.07 \times 10^{-3}\ (x - 726)]\}$; Fraser: $y = 14.0 \times \exp\{-\exp[-2.971 \times 10^{-3}\ (x - 750)]\}$ and Russet Burbank: $y = 15.3 \times \exp\{-\exp[-3.46 \times 10^{-3}\ (x - 667)]\}$. All $R^2 > 0.99$. Vertical dotted line represents the time of 95% final tuber DM for all cultivars.

yield was in the 250 to 450 g range and 25% in tubers larger than 400 g. The average FM tuber weight was higher ($P < 0.001$) for Bondi (238 g) than Fraser and Russet Burbank (114 ± 29).

The three cultivars had 100% emergence. Bondi and Russet Burbank crops emerged ~30 DAP with Fraser 5 d later ($P < 0.001$).

Figure 3 shows the Piece-wise models used to predict the fraction of radiation intercepted (R/R_o) during the crop growing season for each cultivar. These explained over 97% of the variance. The maximum R/R_o was higher ($P < 0.013$) for Bondi and Fraser (~91%) than Russet Burbank. Canopy ground cover increased at a rate of ~0.20% °Cd^{-1} (~2.20% d^{-1}) for all crops. On average the canopy of the cultivars reached their maximum R/R_o after ~500°Cd (~73 DAP) and remained constant at this maximum for a further ~840°Cd (~62 d). Russet Burbank had the fastest ($P < 0.025$) rate of senescence (decrease in green area; 0.15% °Cd^{-1} or 1.60% d^{-1}) and Fraser the slowest (0.06% °Cd^{-1} or 0.63% d^{-1}). However, 95% of the crops final tuber DM yield was reached soon after the canopies started senescing (1350°Cd or 135 DAP). Around that point the accumulated radiation interception was not different ($P < 0.14$) among the cultivars and averaged ~1650 MJ m^{-2} of total solar radiation.

There was no difference ($P < 0.61$) among the cultivars for the amount of radiation intercepted by the canopy per unit of LAI. The critical leaf area index (LAI_{crit}) calculated for when the crops intercepted 90% of the incoming radiation was 3.8 for an extinction coefficient (k) calculated as 0.77 (refer to Appendix G).

The RUE was higher ($P < 0.02$) for Bondi (1.24 g DM MJ^{-1}) than Fraser (0.99 g DM MJ^{-1}), while Russet Burbank averaged 1.09 g MJ^{-1} (Fig. 4).

The pattern of HI increase over time from planting to ~1400°Cd accumulated from crop emergence was exponential for the three cultivars (Fig. 5). The HI was higher ($P < 0.05$) for Bondi and Russet Burbank than Fraser throughout the growth season. After 1400°Cd (around the time of 95% final tuber DM), as the three cultivars had begun to senesce, Fraser

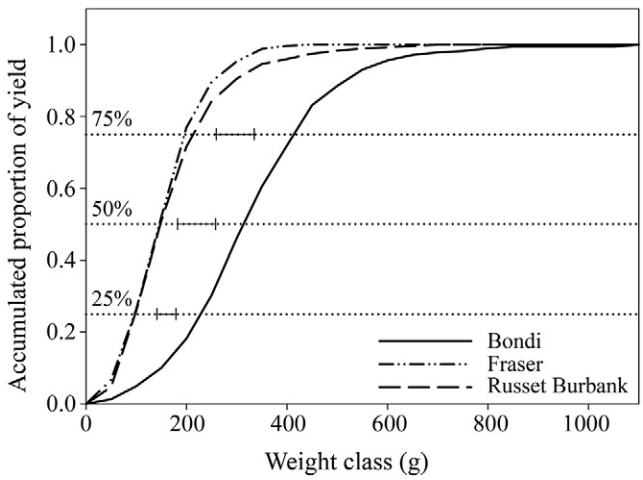

Fig. 2. Accumulated proportions of fresh matter yield against the weight classes at final harvest for Bondi, Fraser, and Russet Burbank potatoes. The crops were grown during the summer (October–May) in the years 2011–2012 at Lincoln, Canterbury, NZ. Horizontal dotted lines indicate the proportion of yield in each quartile. Bars are LSD $\alpha = 0.05$ represented for the accumulated proportion quartiles.

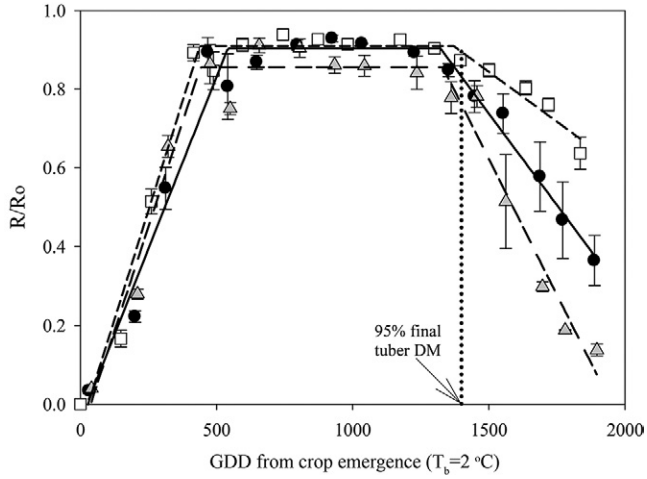

Fig. 3. Fraction of radiation interception (R/R_o) measured from 15 Nov. 2011 to 13 Apr. 2012 against growing degree days (GDD) from crop emergence measured in °Cd for Bondi (closed circle), Fraser (open square) and Russet Burbank (shaded open triangle) potato crops grown between 2011 and 2012. R/R_o from 0 (no cover) to 1 (100% cover). Bars represent the standard error above and below the mean values.

HI averaged 0.74, which was lower ($P < 0.002$) compared with the values found for Bondi (0.83 ± 0.04) and Russet Burbank (0.86 ± 0.04).

The time of 50% fraction of dry matter partitioned into the tubers was different ($P < 0.006$) among cultivars. Bondi and Russet Burbank had 50% of their DM accumulated in the tubers at ~510°Cd from crop emergence (~70 DAP). However, Fraser reached this fraction 17 d later than Russet Burbank (or ~665°Cd from crop emergence).

The leaves accounted for up to ~80% of the aboveground DM (Fig. 6). In most cases, the cultivars increased the DM allocated to their leaves with up to 950 ± 50°Cd accumulated from crop emergence. From then on, leaf DM decreased for Bondi and Russet Burbank, but was relatively constant for

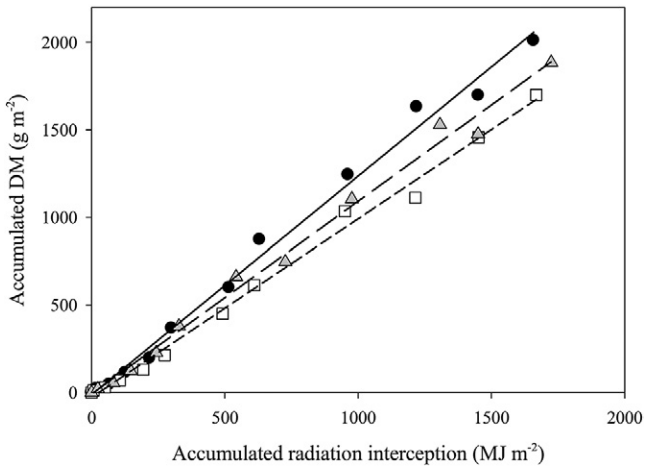

Fig. 4. Accumulated total dry matter (DM) against accumulated total solar radiation interception (R_{cum}) for Bondi (closed circle), Fraser (open square) and Russet Burbank (shaded open triangle) potato crops planted on 14 Oct. 2011. A regression line was fitted to the accumulated total DM against R_{cum} for Bondi: $y = 1.24x$ (0.02), $R^2 = 0.99$; Fraser: $y = 0.99x$ (0.02), $R^2 = 0.99$; Russet Burbank: $y = 1.09x$ (0.02), $R^2 = 0.99$. Bracketed values represent SEM for coefficients.

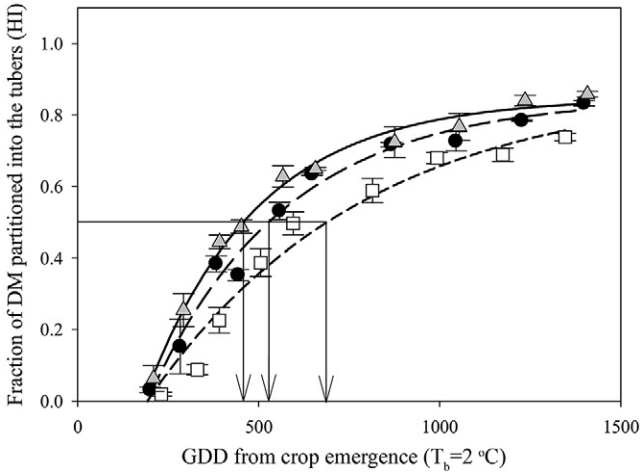

Fig. 5. Fraction of dry matter (DM) partitioned to tubers against cumulative growing degree days (GDD) for Bondi (closed circle), Fraser (open square) and Russet Burbank (shaded open triangle) crops measured from 14 Oct. 2011 to 29 Feb. 2011. Bars represent the standard error above and below the mean values. The exponential curves were fitted to average values for Bondi: y = –0.57 (0.13) + 1.42 (0.10) × {1 – exp [–0.003 (0.0004) x]}, R^2 = 0.99; Fraser: y = –0.34 (0.10) + 1.22 (0.08) × {1 – exp [–0.002 (0.0005) x], R^2 = 0.97 and Russet Burbank: y = –0.68 (0.11) + 1.53 (0.10) × {1 – exp [–0.003 (0.0003) x], R^2 = 0.99. Bracketed values represent SEM for coefficients. Arrows indicate the time of 50% fraction of dry matter partitioned into the tubers.

Fraser. The decrease represented a leaf DM reduction of ~23 and ~13 g plant^{-1} for Bondi and Russet Burbank, respectively. At 1400°Cd the percentage of the aboveground green DM allocated to the leaves was highest (P < 0.001) for Fraser (80% ± 3.5) compared with Bondi (57 ± 3.5%) and Russet Burbank (50.0 ± 3.5%).

All crops had a constant increase in the DM allocated in the aboveground stems up to ~120 DAP. At 138 DAP Russet Burbank had the highest (P < 0.001) percentage of its green aboveground DM allocated in the stems (35 ± 1.7%) compared with Bondi (26 ± 1.6%) and Fraser (18.5 ± 1.7%). Petioles were the lowest aboveground organ pool for DM. These accounted for less than ~15 g per plant in all three cultivars.

Specific leaf area (SLA, m^2 kg^{-1}) change is presented in Fig. 7 as a mean of all leaves measured on the second and third main stem levels. Bondi and Russet Burbank had similar SLA

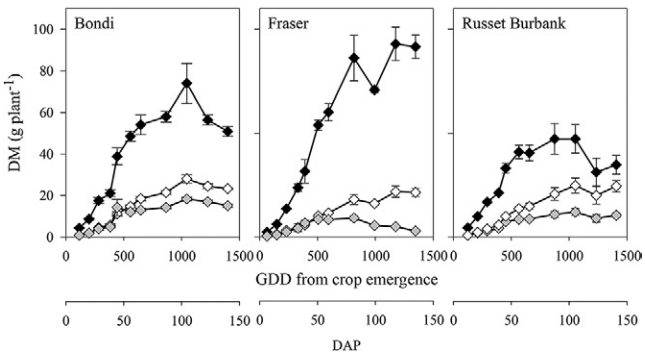

Fig. 6. Pattern of plant dry matter (DM) accumulation in leaf (closed diamond), petiole (shaded open diamond) and stem (open diamond) above the ground level for Bondi, Fraser, and Russet Burbank crops against growing degree days (GDD, T_b = 2°C) and days after planting (DAP) on 14 Oct. 2011. Bars represent the standard error above and below the mean values.

measured from 400 to 1500°Cd. In contrast, Fraser had the lowest values (thicker leaves) for most of this period. Bondi and Russet Burbank reached a maximum of ~24 m^2 kg^{-1} at 650°Cd while Fraser attained a maximum of ~16 m^2 kg^{-1} around that time. In all three cultivars SLA declined after reaching its maximum, but this was less evident in Fraser. Around the time when all cultivars had reached 95% of their total final tuber yield, Bondi and Fraser had a similar SLA of ~13.5 m^2 kg^{-1}.

The pattern of stolon distribution displayed in Fig. 8 shows that the shorter stolons were concentrated on the lower nodes (>6) in all cultivars. Fraser produced the longest (P < 0.001) stolons at the upper middle nodes (1–4). After 40 DAP Russet Burbank had stolons at their maximum length. The same happened to Bondi after 47 DAP. However Fraser maintained stolon growth until ~61 DAP. The sum of all stolon lengths was calculated at 82 DAP to measure the relative distance between phloem and sink. The summed values 82 DAP (Fig. 8) were highest (P < 0.005) for Fraser (354 mm) and lowest for Russet Burbank (190 mm) with 256 mm for Bondi.

The pattern of tuber size distribution at each node position is shown for Bondi, Fraser, and Russet Burbank in Fig. 9. The average values presented correspond only to tubers formed on the primary stolons, since lateral and branched stolons represented <5% of the proportion of tuber initiation.

At 40 DAP only Russet Burbank had signs of tuber initiation on tubers positioned in nodes three, four, and five. Seven and 13 d later these node positions showed signs of initiation in Bondi (47 DAP) and Fraser (53 DAP), respectively. In the three cultivars the top (node one) and bottom nodes had a low (near to zero) chance of initiating tubers. At 82 DAP the most likely (chance > 70%) node positions to initiate a tuber were the third to sixth belowground nodes for Fraser and Russet Burbank, and the fourth to ninth belowground nodes for Bondi. At 82 DAP Bondi had more tubers grown to a longer size (e.g., tubers > 4 cm in length) compared with Fraser and Russet Burbank.

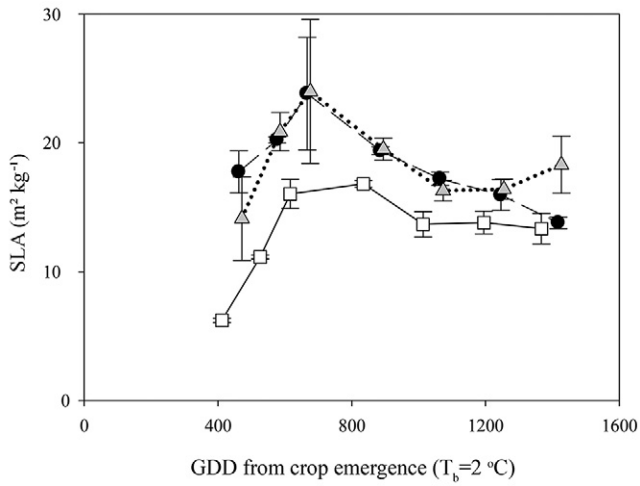

Fig. 7. Mean specific leaf area (SLA, m^2 kg^{-1}) of the second and third levels of the main stem against growing degree days (GDD) from crop emergence measured in °Cd for Bondi (closed circle), Fraser (open square) and Russet Burbank (shaded open triangle) potato crops grown between 2011 and 2012. Bars represent the standard error above and below the mean values.

There is some indication that the tuber length depended on the stolon length to which they were attached. Bondi grew its longest tubers on a stolon of ~20 mm of length, whereas Fraser and Russet Burbank grew them on stolons of ~50 and 40 mm, respectively.

DISCUSSION

Bondi yield was 25% higher than Fraser. These tuber yields were built on radiation interception, RUE, and partitioning. The lower tuber yield capacity for Fraser was associated with its low RUE. This is in accordance with previous findings of contrasting tuber yield potentials among different potato cultivars (Tekalign and Hammes, 2005a, 2005b).

Bondi had the widest grade yield distribution at final harvest (Fig. 2) and the highest average tuber weight. The link between the average tuber size and the spread of distribution has previously been reported (Struik et al., 1991; Searle, 1999). If we define tuber sink strength as the ability of sink organs (or a net C user [Dwelle, 1990]) to accumulate C compounds (Marcelis, 1996), then it is plausible that there is corresponding increase in tuber yield, average tuber weight and tuber sink strength in the present work. This suggests these are inter-related traits (Marcelis, 1996).

Tuber growth rate was higher for Bondi compared with Fraser and Russet Burbank. This attribute influences tuber size distribution (Struik et al., 1990; Struik et al., 1991). It is possible that the tuber bulking in Bondi compensated in a way for the lower plant tuber number (Lynch and Tai, 1989). This implies that the tuber sink strength was related to total tuber biomass accumulation (Engels and Marschner, 1986) rather than the number of tubers, as suggested by Sale (1973). Similar results have been described by Marcelis (1993) for cucumbers (*Cucumis sativus* L.). The implication is that the total sink is the product of tuber number and potential tuber size. Cultivars with a higher total sink strength are then expected to have the highest yield.

For all crops R_{cum} did not affect yield and the spatial and temporal pattern of canopy development was similar (Fig. 3). Specifically at the time of 95% final tuber DM all crops had accumulated the same amount of total radiation (~1650 MJ m^{-2}).

Early crop emergence of Russet Burbank did not lead to the early establishment of the canopy as found by Fandika (2012). In all crops, maximum ground cover was reached after ~500°Cd (~73 DAP). This is in agreement with Spitters (1990) who found little difference among treatments and cultivars as to when maximum canopy ground cover was achieved.

The higher yield of Bondi can be attributed to its high RUE (Fig. 4). This trait was likely to be associated with the highest total tuber sink strength in this cultivar. A positive association between organ sink size (analogous to sink strength), photosynthesis, and RUE has been shown for wheat (*Triticum aestivum* L.) (Blum et al., 1988) and sunflower (*Helianthus annuus* L.) (Sadras et al., 1991). Similar source-sink interactions have also been suggested for potato (Schapendonk et al., 1995; Tekalign and Hammes, 2005a).

Bondi RUE averaged 1.24 g DM MJ^{-1} total intercepted radiation which was 20% higher than for Fraser and ~12% higher than Russet Burbank. The RUE values found in the present study are within the range reported by Manrique et al. (1991) in different parts of the world (0.72 and 1.76 g total DM MJ^{-1} of total solar radiation), but are lower than those exceeding 2 g total DM MJ^{-1} total solar radiation reported for the Tunisian winter by Kooman et al. (1996a).

For a fixed amount of radiation intercepted, RUE can be equated to the rate of gross photosynthesis minus growth respiration (expressed as an efficiency whose value differs depending

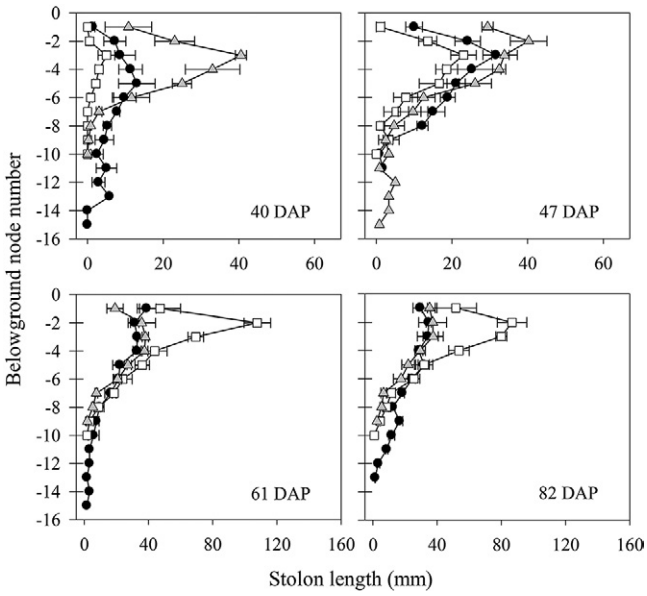

Fig. 8. Average length (mm) of primary stolons at different node positions (number) on the belowground main stem of Bondi (closed circle), Fraser (open square) and Russet Burbank (shaded open triangle) potato crops measured from November 2011 (40 d after planting; DAP) to January 2012 (82 DAP). Bars represent the standard error above and below the mean values.

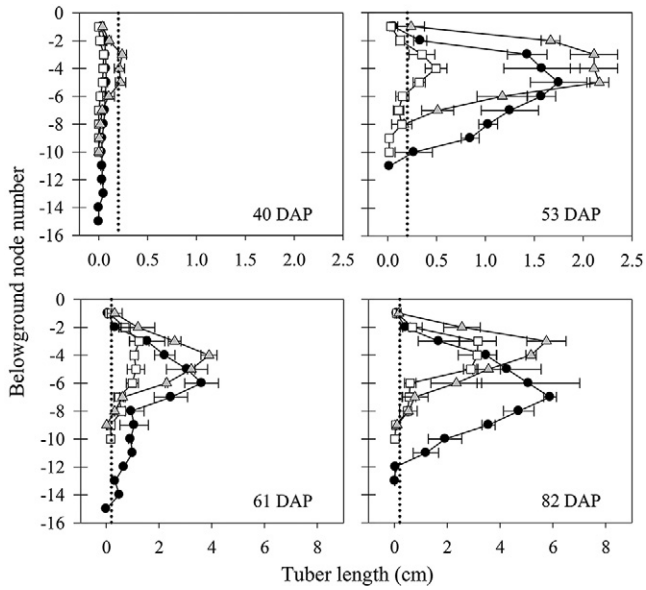

Fig. 9. Mean length (mm) of tubers grown from a primary stolon at different node position (number) on the belowground main stem of Bondi (closed circle), Fraser (open square) and Russet Burbank (shaded open triangle) potato crops measured from November 2011 (40 d after planting; DAP) to January 2012 (82 DAP). Vertical dotted lines indicate tuber initiation (TI) when the tip of the primary stolon had reached 2 mm. Bars represent the standard error above and below the mean values.

on the composition of the biomass being synthesized), and maintenance respiration which consumes photosynthate at a rate that depends on temperature and the amount of existing biomass that is being maintained (Hay and Porter, 2006). The result of this is commonly reported as rate of leaf net photosynthesis. Tekalign and Hammes (2005a), for example, have found different rates of leaf net photosynthesis among different determinate potato cultivars. However, Van Der Zaag and Doornbos (1987) suggested that differences among cultivars in their efficiency to utilize light arise mainly from differences in the rate of photosynthesis, particularly when grown under stress conditions. High temperature (Ku et al., 1977; Timlin et al., 2006), water stress (Van Der Zaag and Doornbos, 1987; Trebejo and Midmore, 1990), non optimum levels of N (Van Der Zaag and Doornbos, 1987; Vos and van der Putten, 1998; Searle, 1999; Shah et al., 2004) and pathogens (Van Oijen, 1991; Shah et al., 2004) have all been linked to low RUE values in potato crops.

However, none of these agronomic factors were present in this study. Thus, it seems likely the RUE difference among these cultivars were physiological rather than agronomic. For example, lower total and individual tuber sink strength for Fraser was shown by its lower LGR. Previous reports have shown a strong correlation between DM yield and net photosynthesis for a range of potato cultivars (Tekalign and Hammes, 2005a). In addition, the progressive increase in leaf DM (Fig. 6) for Fraser may have caused photosynthesis down-regulation in the leaves, thus contributing to a decrease in net photosynthetic rate. Dickinson et al. (1991), for example, associated the excess of C in source leaves of tomato (*Lycopersicon esculentum* Mill.) plants with a block in sucrose translocation. Local sucrose accumulation slows photosynthesis by creating a feed-back limitation of the chloroplast activity when photosynthates are unable to be remobilized from the leaf (Dickinson et al., 1991; Jeuffroy and Ney, 1997; Pessarakli, 2005). It was shown that Fraser maintained a lower SLA (thicker leaves) for most of the period of tuber bulking (Fig. 7). Leaves with low SLA and long life span have lower assimilation rates per unit mass (Reich et al., 1997). These thicker leaves (i.e., lower SLA) may reduce the net C fixation on a leaf mass basis from shaded chloroplasts in the lower parts of the leaf lamella. A second possibility is that an increase in non-structural carbohydrates in some species both decreases SLA and limits C fixation (Meziane and Shipley, 2001). On the other hand, the earlier tuber initiation (Fig. 9) and bulking in Russet Burbank may have led to premature competition for resources thus compromising radiation capacity in this cultivar. Allen and Scott (1980), for example, reported that earliness in potato is accompanied by a lower tuber yield.

The high partitioning rate (Fig. 1 and 5) led Bondi to a higher final tuber yield. It was also shown that around the time of 95% final tuber yield (after all crops had begun to senesce), Bondi had a higher HI (0.82 ± 0.01) than Fraser (0.74 ± 0.02). Previously, Tekalign and Hammes (2005b) found potato cultivar differences in terms of DM allocation to the different plant organs. They also attributed the low tuber dry mass in some cultivars to the poor capacity of DM allocation by this organ.

The higher total tuber sink strength in Bondi compared with Fraser explained the higher tuber DM demand, hence, higher DM partitioning to tubers in Bondi. The high demand was shown by the time of tuber initiation (Fig. 9) being delayed in Fraser compared with the other cultivars. The LGR was ~25% lower in Fraser than Bondi. According to Engels and Marschner (1986) the tuber sink strength in the initial growth phase is determined by the weight of the tubers, as a result of their time of initiation, initial weight and relative growth rate.

It appears that factors which influence "strength" of the tuber sink affect both assimilate allocation and the leaf longevity in potato plants (Kooman and Rabbinge, 1996). In the present study this was illustrated for Fraser. First, its low total and individual tuber sink demand appears to have caused photosynthate to accumulate in the canopy leaves. It was shown that Fraser had a low SLA during the tuber growth phase (Fig. 7) and maintained a high DM concentration in its leaves later in the growth season (~79% of the total aboveground biomass; Fig. 6). If carbon is partitioned into starch in the leaf rather than sucrose it becomes readily unavailable for export from the leaf tissue (Dwelle, 1990) and accumulates in the leaf. This culminates in longer canopy duration, as seen for Fraser, from a low canopy senescence rate (Fig. 3). This result resembles a non-functioning "stay green" (or cosmetic stay green) trait in maize crops with low HI (Kosgey et al., 2013). According to Hörtensteiner (2009), the maintenance of chlorophyll concentration could lead to a reactive oxygen species (ROS) production and cause chlorophyll-mediated photo-destruction. The author suggested that for stay-green individuals this oxidative stress could result in a yield reduction. However, functioning stay-green has been associated to an extension of photosynthetic activity, leading to higher potato yields in drought tolerant genotypes grown under water restriction (Ramírez et al., 2014; Rolando et al., 2015). Further studies could examine the association among tuber sink strength, starch concentration in the leaf and photosynthesis rate under controlled and restricted water conditions.

Unlike seed crops (Feller and Keist, 1986) remobilization from senescing leaves is not central for the nutrient budget in potato crops. Bondi decreased leaf DM after reaching a maximum value (~100 DAP) while Fraser showed no signs of leaf DM depletion (Fig. 6). Nevertheless, this leaf DM remobilization in Bondi represented only 0.8 t ha^{-1} and, thus represented only 20% of the 3.5 t ha^{-1} yield difference.

The longer stolons in Fraser appear to be associated with lower sink strength, and appear to have reduced tuber initiation and growth (Fig. 8 and 9). These stolons (~50 mm) were the site of the larger tubers produced in this cultivar compared with Bondi (~20 mm; Fig. 8 and 9). Therefore, it seems that the production of longer stolons restrained the development of the individual tuber sink strength in Fraser possibly by increasing transport resistance to photosynthates. Similar conclusions were stated by Engels and Marschner (1986) who found a significant correlation between the growth rate of tubers and the volume and cross-sectional area of the phloem. The final size of the stolon has been reported as a consistent genetic trait (Kratzke and Palta, 1992) and crucial for tuber size distribution (Struik et al., 1991). Thus short stolons could be included as selection criteria for the production of larger tubers in potato breeding, or conversely long stolons for smaller tubers to meet a specialist market.

The longer stolons in Fraser may have resulted from a short critical photoperiod (i.e., photoperiod that still permits tuber initiation) trait. This is because in favorable conditions stolon elongation will continue until the time of onset of tuber induction (Brown, 2007). Previous work has shown that long days (or photoperiod; e.g., potato growing season in Canterbury) increases stolon length (Abd El-Hak, 1969) and reduces the induction of tuber initiation (Kooman et al., 1996b). Wheeler and Tibbitts (1997), for example, conducted a growth room experiment with potatoes exposed to different photoperiod regimes. They suggested that higher yields could be achieved by short daylengths during early plant growth; to promote early tuber initiation, followed by high daily photosynthetic photon flux from long days later (at crop maturity) to sustain tuber growth.

Figures 8 and 9 indicate that the sink demand operated within a certain pattern associated with the node position on the belowground main stems, stolon elongation, and tuber initiation. Vreugdenhil and Struik (1989), for example, showed that the earlier formed stolons required a longer period to initiate a tuber compared with the later formed ones. In the present work, the larger tubers were produced in the middle nodes in the belowground main stem profile. This is in agreement with Cother and Cullis (1985). They found that the top and bottom nodes on the belowground main stems were the least likely to bear a marketable tuber (heavier than 45 g). It is possible that the lower nodes on the belowground main stems barely initiate and grow tubers because of their distance from the source. Moreover, tuber growth in the upper node positions (near the soil surface) might be restrained by lower soil moisture and possibly light exposure (Kumar and Wareing, 1972). It was observed that on many occasions the two uppermost nodes (on the belowground main stem) initiated a leaf on the tip of the stolons rather than tubers. Future work could focus on modeling stolon length on the middle nodes in the belowground stems and final tuber yield and distribution.

CONCLUSIONS

Cultivar tuber yield differences were not determined by R_{cum} differences at the end of the season. The tuber sink strength seemed to be causally related to tuber yields. Bondi created the highest tuber sink strength (demand) and maintained the highest RUE (supply). These two traits are probably interrelated. Fraser had the highest R_{cum} at the time of haulm desiccation, but its yield was constrained by the low tuber sink strength and a low RUE maintenance.

The higher sink strength in Bondi was attributed to fewer larger tubers produced in the middle positioned nodes on the belowground main stems. The early tuber initiation in Russet Burbank may have been detrimental to the performance of this crop. The production of longer stolons restrained the development of the tuber sink strength in Fraser possibly by increasing sink resistance to photosynthates. This downregulation seems to be linked to the stay-green leaf trait observed in this cultivar.

ACKNOWLEDGMENTS

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APPENDIX A
Daily Temperature Variation

Figure A1 shows daily minimum, maximum, and average air temperatures between planting and harvesting.

APPENDIX B
Planting Preparation and Management Practices

On 10 Aug. 2011 the areas were plowed and on 6 Oct. 2011 250 kg ha^{-1} of "Cropmaster" 15 (15–10–10–8 N–P–K–S) was surface applied. The site was then rolled and power harrowed. The day before planting, two-row beds were mechanically formed and the soil "conditioned" by removing clods to a narrow channel. A moldboard plow was used to create a trench with 0.3 m of depth in each row. An insecticide Imicacloprid 600 g L^{-1} ("Gaucho") at 3 mL 100 m^{-1} and a fungicide Azoxystrobin 250 g L^{-1} ("Amistar") at 10 mL 100 m^{-1} with 150 L water ha^{-1} was applied on the rows. Fungicide and insecticide applications at the same rate were applied to the crop another 11 and 4 times, respectively, throughout the growth season.

Weed Control

On 28 Oct. 2011 pre-emergent herbicides metribuzin [4-amino-6-*tert*-butyl-3-methylsulfany-1,2,4-triazin-5-one] (Sencor) at 500 g ha^{-1} and cyanazine [2-chloro-4(1-cyano-1-methylethylamino)-6-ethylamino-s-triazine] (Bruno) 2 L g ha^{-1} with 400 L of water were applied for weed control. From 15 Jan. 2012 any weeds emerged in the plots were removed by hand.

Fertilizer Applications

Side-dressings of N fertilizer (urea, 46% N) were applied based on soil test analyses (Table A1), using a hand spinner on 13 and 21 Dec. (100 kg N ha^{-1} each time), and 6 Jan. 2012 (50 kg N ha^{-1}). This was based on a potential potato yield of 20 t DM ha^{-1}, 2% potato N content, and 100 kg ha^{-1} of N required by the plant.

Irrigation

To provide an optimum level of water supply the experiment was irrigated eight times from 21 Dec. 2011 to 2 Feb. 2012 at a 5 to 8 d interval with a total of 30 mm on each application,

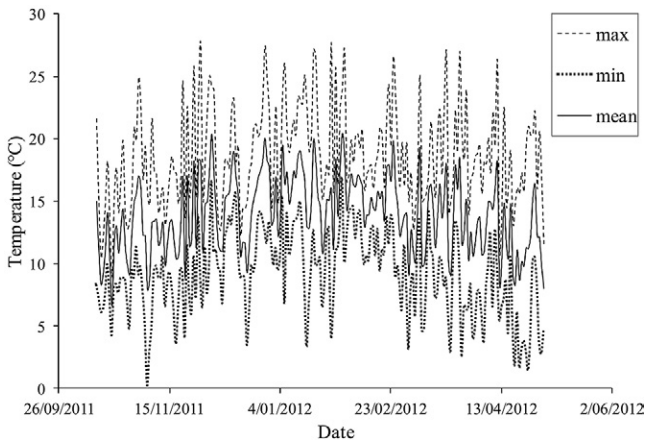

Fig. A1. Average daily maximum, minimum and average temperature measured between planting (13 Oct. 2011) and crop harvest (2 May 2012).

Table A1. Soil test results for the Experimental site in Lincoln, Canterbury, NZ, from 2011. Soils tests were performed using Ministry of Agriculture and Fisheries Quick Test (MAF QT) procedures.†

Nutrient	pH	N	P Olsen phosphate	K	Ca	Mg	Na
		kg ha^{-1}	mg L^{-1}	me 0.1 kg^{-1}			
Soil test	5.8	62	39	0.7	7.94	1.94	0.12
Optimum range	5.4–5.8		30–60	0.50–1.0	4.0–10	1.0–3.0	0.0–0.50

† Soils tests were carried out using the Ministry of Agriculture and Fisheries Quick test (MAF QT). Nitrogen value represents mineralized N available in the soil. me = milliequivalents.

Table A2. Grade and total tuber fresh weight yields of Bondi, Fraser, and Russet Burbank potato crops grown from October to May 2011–2012 at Canterbury, NZ.†

	Seed grade				Table grade		Process grade (premium)							
	0–50 g		50–113 g		113–170 g		170–250 g		250–350 g		>350 g		Total potato	
Cultivar	Yield	No.	Yield	No.	Yield	No.	Yield	No.	Yield	No.	Yield	No.	Yield	No.
	t ha^{-1}	m^{-2}	t ha^{-1}	m^{-2}	t ha^{-1}	m^{-2}	t ha^{-1}	m^{-2}	t ha^{-1}	m^{-2}	t ha^{-1}	m^{-2}	t ha^{-1}	m^{-2}
Bondi	0.90	2.70	3.30	4.10	4.10	2.9	11.8	5.60	20.0	6.70	26.0	5.8	66.1	27.8
Fraser	3.40	11.1	12.3	15.6	16.2	11.6	13.8	6.90	5.00	1.70	0.6	0.20	51.3	47.2
Russet Burbank	2.40	7.10	14.2	17.6	13.9	10.0	13.0	6.50	5.50	1.90	3.10	0.70	52.0	43.7
P	0.003	0.002	<0.001	<0.001	<0.001	<0.001	ns	ns	0.002	0.003	0.003	0.002	0.067	0.006
LSD	0.85	2.62	1.96	2.40	3.08	2.11	3.25	1.56	5.33	1.86	9.5	1.93	13.6	8.2

	French fry (>113 g)	
Cultivar	Yield	No.
	t ha^{-1}	m^{-2}
Bondi	61.9	21.0
Russet Burbank	35.4	19.0
P	0.02	0.05
LSD	15.01	1.88

† No., number of potatoes; LSD = least significant difference. The comparison of tuber yield and numbers in the French fry grade does not include Fraser which is grown for crisp potato.

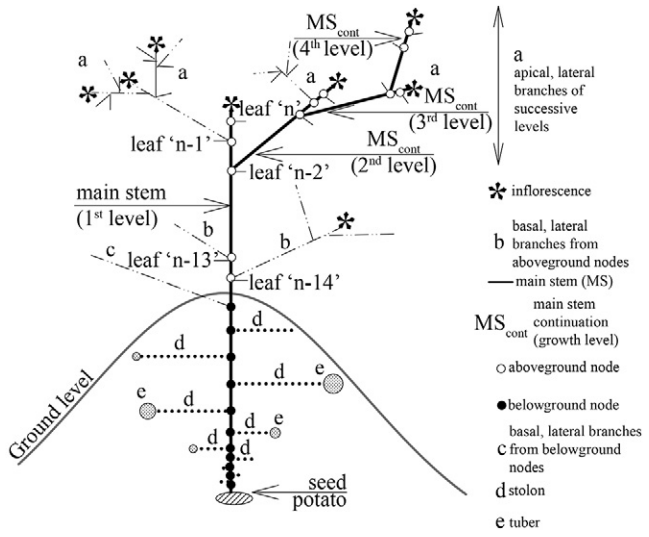

Fig. A2. Simplified diagram of one main stem produced by the seed potato with all its different organs (stolons, tubers, branches, leaves, and flowers), but excluding roots. Revised after Vos (1995) and Struik and Ewing (1995).

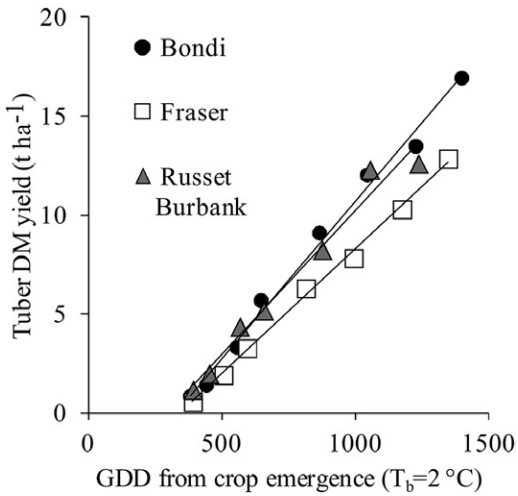

Fig. A3. Accumulated total dry matter (DM) against growing degree days (GDD) for Bondi, Fraser, and Russet Burbank potato crops planted on 14 Oct. 2011. A regression line was fitted to the accumulated total DM against GDD using all data-points within the range of 5 and 95% of the maximum yield for each cultivar: Bondi: $y = 1.58 \times 10^{-2} x - 517$, $R^2 = 0.99$; Fraser: $y = 1.26 \times 10^{-2} x - 435$, $R^2 = 0.99$; Russet Burbank: $y = 1.44 \times 10^{-2} x - 425$, $R^2 = 0.98$.

using a linear irrigator. The amount applied was based on the average daily potential evapotranspiration (E_{po}) of 4.0 mm d^{-1} (averaged from October to May) calculated from a long-term data series from 1960 to 2012.

In addition the irrigation was timed to prevent the actual soil moisture deficit from exceeding 60 mm in the top 400 mm of soil. The water stress threshold of 60 mm was calculated based on field capacity of about 30% (Yunusa et al., 1995), 400 mm of root depth and 50% of soil water capacity available to the plant.

APPENDIX C

Schematic Illustration of the Potato Plant

A schematic diagram detailing only one main stem (grown from the seed potato) with its different organs (stolons, tubers, branches, leaves, and flowers) is shown in Fig. A2.

APPENDIX D

Normalized Difference Vegetation Index Calculations

NDVI was calculated according to Eq. [B1]:

$$NDVI = (NIR - VIS)/(NIR + VIS) \quad [B1]$$

The NIR and VIS wavelengths measured from the instrument and used to calculate the NDVI were 760 and 660 nm, respectively. All reflectance measurements were obtained between 1000 and 1500 h, based on local time during clear sky conditions. The potato canopy area for each assessment covered a circle 0.8 m in diameter. The NDVI reading were done with the CropScan sensors attached to a probe placed between the two rows of each plot. A bare soil reading was taken on the day of each measurement. There was a need to transform the NDVI reading to estimate the maximum cover and correct the values for bare soil reflectance. This is because bare soil readings ranged from 0.09 to 0.11 NDVI which overestimated canopy cover during the early phase of canopy expansion (right after crop emergence). Moreover, from visual assessments it was noticed that the maximum canopy ground cover readings underestimated the maximum cover achieved by the canopy ($R/R_o = 0.95$). Therefore, R/R_o was corrected for each plot using the NDVI values calibrated according to Eq. [B2]; based on Carlson and Ripley (1997):

$$R/R_o = (NDVI_r - NDVI_s)/(NDVI_{max} - NDVI_s) \times C_{max} \quad [B2]$$

where $NDVI_r$ is the Index measured on the crop, $NDVI_s$ is the Index measurement on a bare soil, C_{max} is the actual maximum crop canopy cover and $NDVI_{max}$ is the highest NDVI reading for the plot throughout the season. C_{max} was considered 0.95 for the calculations. It follows that, when $NDVI_r$ equalled $NDVI_s$ the NDVI values were fully from the bare soil (no canopy), thus R/R_o equalled zero. However, when the plot reached maximum canopy reading ($NDVI_{max}$), R/R_o equalled 0.95.

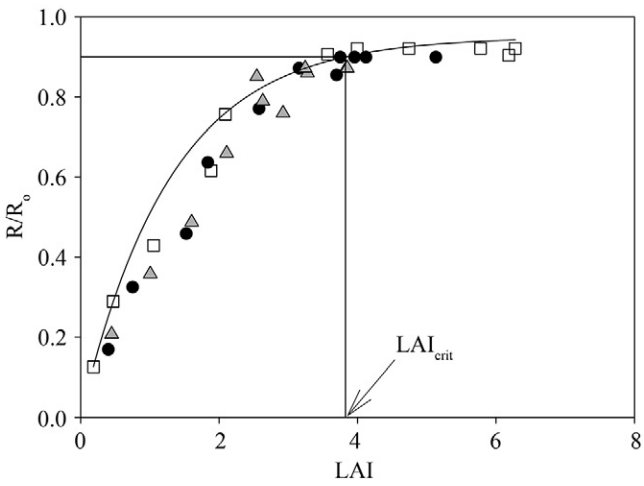

Fig. A4. Radiation interception (R/R_o) against leaf area index (LAI) for Bondi (closed circle), Fraser (open square) and Russet Burbank (shaded open triangle) potato crops from 23 Nov. 2011 to 29 Feb. 2012. Regression $R/R_o = 0.95$ [1– exp (–0.77x LAI)], $R^2 = 0.97$. Slope standard error = 0.02.

APPENDIX E

Linear Growth Rate

Linear growth rate was calculated by fitting a linear regression between accumulated tuber DM against GDD using all data-points within the range of 5 and 95% of the maximum yield for each cultivar is depicted in Fig. A3.

APPENDIX F

Marketable Tuber Yield and Number

Grade FM yield, total FM tuber yield and number differences among Bondi, Fraser, and Russet Burbank are shown in Table A2.

APPENDIX G

Leaf Area Index and Extinction Coefficient

Figure A4 shows the regression fitted between leaf area index (LAI) and the fraction of radiation interception (R/R_o) for a coefficient (k) of 0.77.

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